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STAR CLUSTERS AND THEIR CONTRIBUTION TO KNOWLEDGE OF THE UNIVERSE.

By HARLOW SHAPLEY.

(*Read April 25, 1919.*)

Social relationships among stars are nearly as common as among men and the lower animals. Sidereal bodies completely independent of all star societies are difficult of conception; for the heritage of early and ancestral associations, as well as the immediate environment, influences the present behavior and the destiny of stars. Planetary systems, binaries, groups of three or four nearly equal bodies are thought to be very common—almost universal, it may be; and the assemblage of stars of all kinds by the tens, hundreds, and thousands into physically organized clusters now appears to be a property of fundamental significance in stellar investigations.

In considering the aspect of clustering among the fixed stars we see a gradual progression from the largest and most scattered constellations to such rich and highly concentrated stellar groups as the globular clusters. Although the constellations were outlined for the most part in prehistoric times and have been used in myths and astrology persistently and universally throughout thousands of years, in general they do not represent definite physical organizations that exclude the stars of neighboring groups; and frequently even the legendary relationships of the stars in the most anciently known constellations are traced with difficulty.

There is, however, among the varied groupings, an easy transition from widely-scattered Ophiuchus and Camelopardalis to Orion, Scorpio, and the Great Bear; and in recent years we have found that the most conspicuous stars of these three last named constellations actually form physical stellar systems. The stars of each have motion, colors, and distances much in common, and in each case they have evolved, no doubt, from an origin common in space and in time. From Orion we readily trace the progression in clustering

to the Hyades—a more compact and more definitely circumscribed dynamical system—and then to the Pleiades, to Præsepe, to the double cluster in Perseus and similar faint loose clusters of the Milky Way; thence, by way of Messier 11 and Messier 22, we proceed by nearly equal steps to the typical globular systems exemplified in the great Hercules cluster, Messier 13.

Although we may justly restrict the term "star cluster" to physical systems—that is, to groups which have the characteristics of distinct dynamical organization—it is clear that the subdivisions of the long sequence of groups from Orion to the Hercules cluster must necessarily be vaguely defined. For convenience we here distinguish only open and globular clusters, and designate all as open except those seventy or eighty highly condensed groups whose stars appear innumerable even with the aid of our biggest telescopes and most sensitive photographic plates.

Open and globular clusters differ in matters other than richness and apparent circularity. In average distance from the earth the globular clusters much excel, in stellar constituency they are more varied, and we recognize in their wide spatial distribution that from a dynamical point of view the globular clusters are quite distinct from the open groups which closely congregate along the middle line of the Milky Way.

A few of the nearest globular clusters are visible to the unaided eye as faint hazy objects, and some of them have been in the astronomical records for two or three hundred years. To Messier and earlier observers they were known only as starless nebulosities, but Sir William Herschel and his son, with their greater telescopes, partially or completely resolved the brighter clusters into myriads of distinct stars.

The great telescopes of the present time and the powerful modern methods of astrophysical investigation have greatly extended our knowledge of globular clusters, but they have not appreciably added to the total number. The numbers of known stars and nebulæ have increased enormously with the increase of optical power, but during the last eighty years less than five new globular clusters have been added to the original lists compiled by the Herschels. In fact, we seem to have passed the era of discovery of such systems; the pres-

ent lists may be considered essentially complete—a condition that does not prevail for any other important type of celestial object.

It has been shown through the studies made at Mount Wilson that most of the globular clusters are remotely isolated systems, neither intermingled with nor closely surrounded by other stars. They may be treated, indeed, as distinct cosmic units; and in treating them as such, we may fulfil the purpose of the present communication by discussing briefly a single system. In certain details, there are, to be sure, conspicuous differences from system to system, but in such matters as size, number of stars, and stellar make-up, no greater diversity appears.

The Great Cluster in Hercules, No. 13 in Messier's well-known compilation of 103 bright nebulæ and clusters, is the system chosen for the present illustration. To the unaided eye it is faintly visible as a hazy star of magnitude 5.8, about two degrees south of Eta Herculis. The photograph used for this illustration was made by Professor Ritchey on a plate of medium rapidity with an exposure of eleven hours; it records something like 30,000 stellar images brighter than the twenty-first magnitude. Nearly all of these are actual members of the cluster and not merely objects of the foreground, projected among the cluster stars.

The distribution, brightness, and colors of many hundreds of the stars in Messier 13 have been specially studied at Mount Wilson. Some attention has also been given to spectral types and radial velocities—difficult problems even for large telescopes and powerful spectrographs because of the extreme faintness of the individual stars. Space cannot be given here to describe the methods recently developed for the determination of the distance of Messier 13 and other globular clusters; we shall only remark that photometry, astrometry, and spectroscopy are all involved, and that Cepheid variable stars play a fundamental rôle. The adopted value of the parallax for the Hercules cluster is $0''.00009$, with an estimated uncertainty of less than twenty per cent.

Even to those who are accustomed to think of the great depths of sidereal space, it is difficult to comprehend clearly the remoteness of the Hercules cluster. Its distance, 3.5×10^{17} kilometers, is more than eight thousand times that of the nearest star now known.

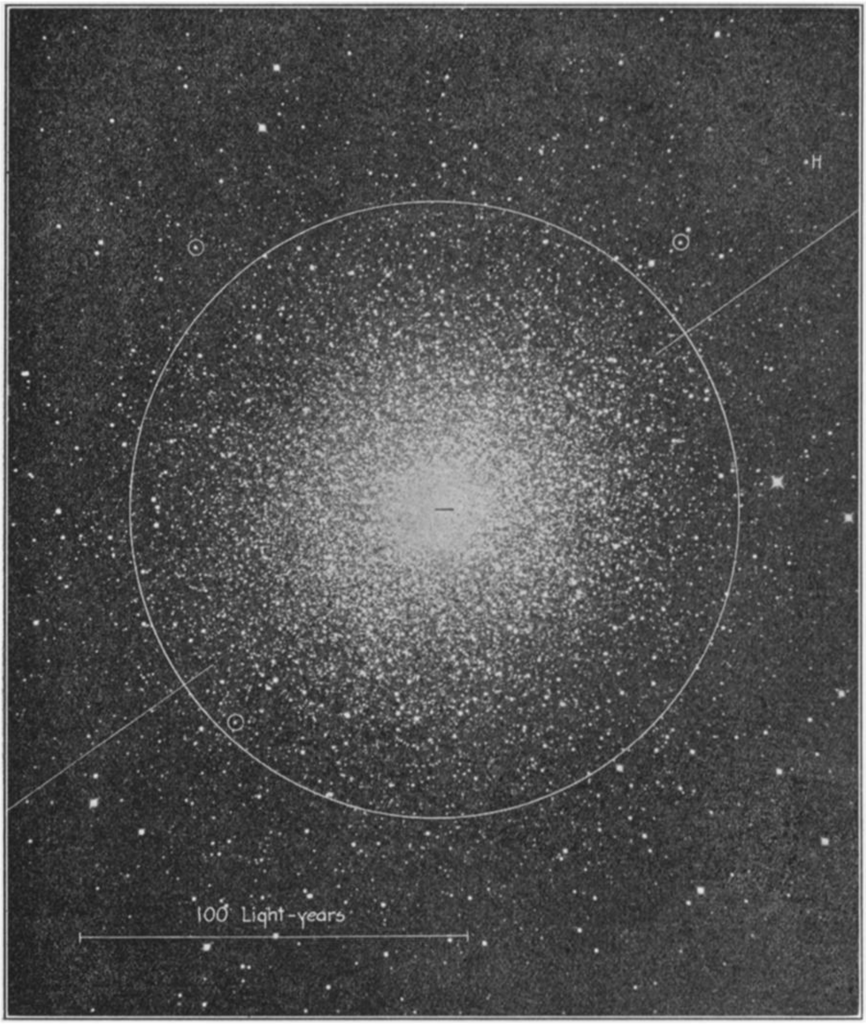

FIG. 1. The Globular Cluster, Messier 13.

Light, traveling with its hardly conceivable velocity of 300,000 kilometers in a second of time, requires eight minutes for the passage from the sun to the earth, but it must travel more than two thousand million times as long to reach us from this globular cluster. Hence our knowledge of the position and physical characteristics of Messier 13 does not refer to the system as it now exists. Our

most recent information dates from the time the light we now receive left its remote origin in the cluster, and what has occurred there during the last 360 centuries is beyond our power of finding out. On the basis of our knowledge of the probable causes of these past conditions, we may believe with good reason that the cluster is now much as it was 36,000 years ago. Such an interval of time is of small consequence in the life history of a gigantic stellar system; but while these pulses of light have been coming across the intervening fraction of unending space a thousand human generations have come and gone; man has emerged from a vague, unrecorded past and in fleeting succession all his historically known national civilizations have slowly evolved, flourished in vaunted permanence and supremacy, and quickly relapsed into oblivion or poor mediocrity. We recall, too, that of all the globular clusters whose radiation is continually streaming toward the earth, Messier 13 is one of the very nearest.

With the distance of the cluster known, we readily translate angular dimensions, as measured on the surface of the sky, into linear dimensions. Thus, by the definition of parallax, the angular value $0''.00009$ corresponds in the Hercules cluster to one astronomical unit—the distance separating sun and earth. By transferring a linear scale to the cluster, therefore, as in the accompanying illustration (which does not include the outlying stars), we may determine the separation of the individual stars, the number in a given volume, and numerous other facts concerning the physical structure of the system.

It is worthy of emphasis that in determining the distance of the Hercules cluster we have at the same time derived the distances of its tens of thousands of stars. The absolute values of these distances appear to be accurately known; and certainly the distances of these stars relative to each other are known with an accuracy that is unequalled in ordinary parallax work, for in any given globular cluster the distance of all the stars from the earth may be accepted as the same, with an error of less than one per cent. We are thus in a position to make some general investigations of the inter-relationships of the brightness, colors, numbers, and positions of stars; and, because of so little uncertainty in the relative distances

and because of the great numbers of stars available, we can make these investigations with more ease and accuracy in a globular cluster than with the bright stars around the sun.

A conception of the great size of a globular cluster may be gained by indicating on the picture of Messier 13 some of the familiar distances of the solar neighborhood. The distance separating the nearest known star (Alpha Centauri) from the sun is indicated by the short black line near the center. In the cluster, within the corresponding distance from the center, there appear to be thousands of stars, illustrating how greatly different from the conditions of our own immediate part of the universe is the concentration of mass and luminosity in a globular system. The distance to the Hyades, the well-known group of bright stars in Taurus, is represented on the photograph by the distance from the center of the cluster to the star marked *H*. The diameter of the large circle is about fifteen minutes of arc on the surface of the sky, corresponding at the distance of the cluster to ten million astronomical units; a sphere of that diameter with the sun at the center would include all the stars within eighty light-years.

The total angular diameter of the cluster is about thirty-five minutes of arc, corresponding to twenty-three million astronomical units, or more than three hundred and fifty light-years.

All the cluster stars shown on the photograph are giants in actual luminosity. At the cluster's distance of 36,000 light-years, a star as bright as our sun would be considerably fainter than the twentieth magnitude and would not appear on this reproduction. The three stars whose images are enclosed in small circles are photographically almost exactly one hundred times as bright as the sun, and the most luminous giants in the cluster exceed a thousand suns in light emission.

It is a remarkable fact that the brightest of these cluster stars are red and the fainter ones are blue. The red stars, because of low surface temperature, emit much less light for a given amount of surface area. To excel in brightness, therefore, their volumes must be enormously large—in extreme cases more than a hundred thousand times that of the sun, and, since stellar masses in general are probably not very unequal, the mean densities of these red giants are correspondingly small.

Although these cluster stars are gigantic when compared with the sun, and are highly concentrated into a compact and symmetrical organization, they do not differ in physical properties, so far as we now can tell, from hundreds of isolated stars of the Galaxy. Many of the naked eye stars equal them in light power, in color, in volume. The Cepheid variables in the cluster have light-curves, color variations, and spectra like those of the variables near the sun. In other words, the members of clusters are normal stars.

Until recently the globular clusters have been accepted as spherical in shape. When projected on the sky we should therefore expect them to be circular in outline, and, except for accidental errors of distribution, the number of stars should be the same whatever the direction from the center. A systematic study of the photographs at Mount Wilson has shown, however, that a majority of globular clusters, as seen in the sky, are slightly but symmetrically elongated. This condition has been interpreted as a flattening of the cluster system—an indication that the clusters are not spheres. but rather are oblate spheroids or ellipsoids. Messier 13 is one of the most flattened; and though the elongation, in the direction indicated in the picture by inclined white lines, can be uncertainly seen, either visually or on photographs of the cluster, it is very readily shown by counts of the individual stars. There are about thirty per cent more stars in the direction of elongation than at right angles thereto.

The flattening suggests that this great stellar system may be in rotation about its shorter axis. Observations have not as yet determined whether or not such a motion exists. It is known, however, from spectroscopic work at the Lowell Observatory and at Mount Wilson, that the cluster as a whole is moxing with the high velocity of two or three hundred kilometers a second. Noting that the mass of the whole cluster is probably in excess of 100,000 suns, we appreciate that the momentum of this moving cosmic unit must be exceedingly great.

The only component of the motion of Messier 13 now known is directed toward the earth and toward the greatly extended strata of stars that constitute the galactic system. If the cluster moves constantly with this velocity, it will have reached the galactic plane within fifty million years, coming from its present isolation in space

to the regions where scattered galactic stars are numerous and where all the open clusters are found.

The foregoing analysis of a single typical globular system indicates the relevancy of the investigation of clusters to general stellar problems. The factor that contributes most to knowledge of the sidereal universe naturally is that of distance, for distance is the key to the actual dimensions of a cluster and to the real luminosity of stars. We directly approach problems of even greater interest, however, when the distance is determined not only for Messier 13 but also for the 85 other globular systems that are now recorded in our catalogues. Those problems are the size of the known stellar universe, and the arrangement and relationships of its various parts.

Probably the most interesting of many results deduced from the study of the aggregate of open and globular clusters is the evidence of the insignificance of the earth, sun, and brighter stars in the general galactic system. We are impressed with the shortness of the sidereal distances commonly measured as compared with those of clusters, Cepheid variables, and star clouds. The sun, it appears, is only a yellow, dwarfish, very old star, eccentrically situated in a large moving star cluster which is itself situated still more eccentrically in an immensely larger stellar organization—that is, in the general galactic system, which appears to include practically all known objects of the stellar universe.

The details and general results of the investigation of the distances and distribution of all globular clusters cannot be mentioned here; but we may conclude and briefly summarize by stating that the study indicates that in volume the galactic system is more than a hundred thousand times as large as we formerly believed it to be. The center of the great ellipsoidal system appears to lie in the direction of the rich star clouds of Sagittarius, at a distance of at least sixty thousand light-years. Its most striking feature, besides its dimensions and probable mass, is the extensive, much flattened, mid-galactic segment, which contains open clusters, isolated stars, and nebulæ in abundance, but appears to be empty of globular clusters. Apparently the globular clusters are approaching this segment from without—their radial motions, their distribution in space, and their

probable genetic relationships to open clusters support that view. It may be that the thousands of sub-organizations in the galactic system, such as open clusters, star streams, moving groups like those in Ursa Major and Taurus, wide pairs of stars of common motion, long-period visual binaries, all oringinate in these in-falling globular clusters; it may be, too, that the galactic system itself, which possibly is little else than a great mixture of disintegrating minor systems, owes its beginning and subsequent growth to globular clusters. But whatever its origin and destiny, it is clear that the sidereal system, as it now stands out, is a giant in mass and volume compared with the region around the sun to which we have usually confined our stellar investigations.

MOUNT WILSON OBSERVATORY,
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